

# Carbon Emission Efficiency and Emission Permit Allocation of China's Fire Power Industry: An Emission Permit Trading Perspective

Caifeng S<sup>1</sup>, Chu J<sup>1</sup> and Wu J<sup>2</sup>

<sup>1</sup>Central South University, China

<sup>2</sup>University of science and technology of China

**Corresponding author:** Caifeng S, Central South University, China, Tel: +86-18756020065, E-mail: shaocaifeng@csu.edu.cn

**Citation:** Caifeng S, Chu J, Wu J (2022) Carbon Emission Efficiency and Emission Permit Allocation of China's Fire Power Industry: An Emission Permit Trading Perspective. *J Environ Pollut Control* 5(1): 104

**Received Date:** January 19, 2022 **Accepted Date:** February 08, 2022 **Published Date:** February 12, 2022

## Abstract

The emissions trading system is an important tool to combat climate change, which uses the “cap and trade” principle to reduce carbon dioxide emissions. This paper first adopts production technology considering carbon emission permit trading and proposes a data envelopment analysis (DEA) model to evaluate carbon emission efficiency of Chinese fire power industry from 2013 to 2017. Further, a new zero sum gains DEA (ZSG-DEA) considering carbon emission permit trading model is proposed based on efficiency principle to adjust the initial allocation of carbon emission permits (considering fairness principle) among regional fire power industries in 2030. The new approach enables us to investigate the carbon emission efficiency and emission permit allocation problem from an emission permit trading perspective. Theoretical analysis show that organizations have higher potential in reducing carbon emissions and greater potential in improving inputs and outputs after introducing emitting permit trading. Empirical results show that the southeastern fire power industries have higher carbon emission efficiencies and permitted emission levels. Under the background of carbon emission permit trading, the allocation level of carbon emissions permit in inefficient areas is limited and given greater responsibility for reducing emissions considering fairness and efficiency principles. This could promote active carbon emissions reduction in various regions so as to realize China's carbon emissions [1] reduction targets in a faster pace.

**Keywords:** Carbon Emission Permit Trading, Carbon Emission Permit Allocation, Carbon Emission Permit Trading Price, Data Envelopment Analysis, ZSG-DEA

## Introduction

In recent years, human activities (for instance, industrial activities) have emitted huge amount of greenhouse gases to the air, resulting in the serious problem of global warming. One of the main components of greenhouse gases is carbon dioxide (Zhang et al,2020) [2]. Recognizing the importance of protecting the environment and the necessity of reducing greenhouse emissions, many countries have conducted relative actions and policies to control emissions. China currently has the most carbon dioxide emission in the world (Wang et al., 2015; Lee, 2019) [3,4], but China has taken great initiative to undertake emission reduction responsibilities. The country has launched carbon emission permit trading system in 2017 and the carbon dioxide emission permit trading market was initially established (<http://www.tanpaifang.com/>). Moreover, China's 2020 carbon emission abatement target has been achieved ahead of schedule and China proposed the goal of "carbon peak by 2030 and carbon neutral goal by 2060", which show that China's emission reduction actions have achieved certain results (Wang et al., 2021) [5]. We all know that China will reach the peak of carbon by 2030, so China's emission reduction task is still very heavy. It is very meaningful to study the impact of China's carbon permit emission trading market on the domestic carbon emission industry and the promotion of emission reduction.

The above special market-- carbon dioxide emission permit trading market, allows companies to sell and buy carbon emission permit, which incents companies to reduce carbon emissions. It provides a platform for organizations to acquire additional emission permit to fulfill production requirement (Dai and He,2018) [6]. Moreover, the carbon emission permit trading market may bring potential income for some companies with additional carbon emission permit. For example, Tesla's revenue from selling emission permits was 1.6 billion US dollars in 2020, which exceeded the net profit of the company in that year and became one of its main profitable businesses. So, the carbon emission permit trading may affect the organization's carbon emission performance and the allocation of carbon emission allowances.

Reasonable allocation of emission permits should not only fully consider the organizations practical productions situations but also promote the realization of overall emission reduction target. Therefore, proposing efficient and fair carbon emission permits allocation approaches becomes essential. At present, the methods commonly used to study carbon emission allocation can be mainly divided into the following three categories: grandfathering method, output-based allocation, and the DEA-based method. The grandfathering method is now the most famous method for emission permit allocation in oversea due to its convenience, which assigns carbon emission permits only based on the historical cumulative carbon dioxide emissions of each organization (or decision-making unit (DMU)) (Goulder et al, 1999) [7]. But this means that more carbon emission permits are allocated to DMUs that emit more, which gives the sense of unfairness and makes the results not acceptable to most of the DMUs, especially, for the DMUs that have endeavored investments in reducing carbon emissions. More importantly, under the background of emission permit trading, the emission permits allocated to a DMU could be regarded as its resources, such resources (if not fully used) can be traded in the market to generate additional revenue (or value), which makes the grandfathering method even more unsupported by participators.

Output-based allocation method (Fischer and Fox, 2004; Takeda et al., 2014) [8,9] allocates emission permits according to organization's current desirable output level. However, this method only considers outputs of the organizations when making emission permit allocation and ignores the input factors, which may lead to undesired results of increased emissions (Momeni et al., 2019) [10].

DEA is a nonparametric and data-driven method, which has been widely applied for organizational efficiency evaluation and carbon emission permit allocation since the first development of the constant returns to scale (CRS) DEA model (Charnes et al., 1978) [11]. There are many DEA methods to allocate carbon emission or permits. For example, Lozano et al. (2009) [12] considered maximizing the total expected output, minimizing the overall undesired emissions, and minimizing consuming input in three phases by traditional DEA to reallocate emission permits. Sun J et al. (2014) [13] believe that maximizing individual permits in Lozano et al.(2009) [12] is a drawback, so they maximized its allowable carbon emission permits when considering the allocation of carbon emission permits not only from an individual perspective but also centralized perspective. Feng et al. (2015) [14] calculated the allocation of carbon emission abatement by considering that the largest overall benefits under the two-scale returns and introducing

two compensation mechanisms to ensure individual interests as much as possible. Wu, J et al. (2016) [15] proposed two two-stage network DEA method (considering some special input or output properties) to get total optimal carbon emission abatement level and allocate it by combining the farthest and the nearest goal setting. Yu, A et al. (2019) [16] considered regional collaboration after minimizing abatement cost and maximizing potential income by DEA to allocate industrial carbon abatement allocations. Du, J et al.(2020) [17] proposed a new directional distance function methodology considering two principles and developed an iterative procedure to allocate carbon emission allowance.

Except the above DEA-based emission permit allocation method, ZSG-DEA is often applied for carbon emission allocation because the method can evaluate the efficiency of carbon emission allocation. The ZSG-DEA model was first proposed by Lins et al. (2003) [18] for the efficiency evaluation of each participating country under total number of Olympic Games medals. Gomes and Lins (2008) [19] improved original ZSG-DEA to investigate carbon emission permit allocation. They considered the cooperation among inefficient DMUs and distributed the all inefficient parts proportionally to the efficient DMUs. Lin and Ning (2011) [20] adopt a competitive relationship among the DMUs on the allocation of carbon emission permit and build the new ZSG-DEA model. Yang et al. (2020) [21] revised the approach of Lin and Ning (2011) [20] to consider carbon emission permits allocation among 20 Chinese provincial regions in 2020. Miao et al.(2016) [22], Zhang et al.(2017) [23] and Yu et al.(2019) [24] also adapt ZSG-DEA model to allocation results.

The above studies have enriched both mechanisms and methods for carbon emission permits allocation. We know that China started carbon emission permit trading system activities in 2013 and launched carbon emission permit trading activities nationwide in 2017. However, there still lacks corresponding studies which investigate the carbon emission permits allocation problem considering emission permit trading. Therefore, we introduce this background to study the allocation of carbon emissions. The innovative production technology (or, production possibility set), developed by Chu et al. (2021) [25], is adopted as theoretical framework to build models for carbon emission efficiency evaluation of the DMUs considering emission permit trading. Further, we propose a new ZSG-DEA model to study the allocation of carbon emission permits among the DMUs because of objectivity of ZSG-DEA(Pang et al.,2015). The proposed approach is further applied to improve the designed 2030's initial carbon emission allocation scheme of China's fire-power industry.

The remainder of this paper mainly consists of the following parts: Section 2 presents production possibility set by introducing carbon emission permit trading and proposes models for carbon emission efficiency evaluation and allocation efficiency improvement of the DMUs. Section 3 describes data and predicts the inputs-outputs of fire power industry in 2030. Section 4 evaluates the efficiency of carbon emissions from 2013 to 2017 and explores the optimal carbon emission allocation in China in 2030 considering fairness and efficiency principles. Section 5 conducts the sensitivity analysis of carbon emission permit trading prices and discusses the impact of carbon emission permit trading on allocation of carbon emission. Finally, the last section discusses and concludes the study.

## Methods

### Production possibility set considering carbon emission permit trading

Production possibility set is the basis for building DEA models. Considering that the existence of carbon emission permit trading may affect the original production of DMU, we adopted the following production possibility set-T in formula (1). In production possibility set-T,  $DMU_j$  stands for the  $j^{th}$  DMU. Before production, a total carbon emission permits are allocated to  $n$  DMUs,  $DMU_j$  ( $j = 1, 2, \dots, n$ ) consumes  $m$  inputs  $X_j = (x_{1j}, x_{2j}, \dots, x_{mj})$  to get  $r$  desirable outputs  $Y_j = (y_{1j}, y_{2j}, \dots, y_{rj})$ , one monetary output  $g_j$  and one undesirable output  $b_j$ . Formula (1) is the complete production process considering carbon emission permit trading, which satisfies feasibility, convexity, free disposability and emission permit trading (Chu et al. (2021) [25]). The advantage of this production possibility set is that it includes the influence of emission permit trading on DMUs' production technology. In Section 5, we will analyze the role and influence of the carbon emission permit trading on the production process.

$$\begin{aligned}
 T = \{ & (X, Y) \mid \sum_{j=1}^n (\lambda_j + \mu_j) X_j \leq X, \sum_{j=1}^n \lambda_j Y_j \geq Y, \\
 & \sum_{j=1}^n (\lambda_j g_j + c \mu_j b_j) \geq g, \sum_{j=1}^n \lambda_j b_j = b, \\
 & \sum_{j=1}^n (\lambda_j + \mu_j) = 1, \lambda_j \geq 0, \mu_j \geq 0, \forall j \}
 \end{aligned} \tag{1}$$

### Models and methods considering carbon emission permit trading

Here, we first use the production possibility set in Section 2.1 to construct the BCC model combining with Banker et al. (1984) [26] to obtain an undesired output-oriented efficiency evaluation model considering carbon emission permit trading, namely, model (2).

$$\begin{aligned}
 \text{Min} & & & & & & & \theta_d \\
 & & & & & & & \\
 & & & \sum_{j=1}^n (\lambda_j + \mu_j) x_{ij} \leq x_{id}, & i = 1, 2, \dots, m & & (2a) \\
 & & & \sum_{j=1}^n \lambda_j y_{rj} \geq y_{rd}, & r = 1, 2, \dots, s & & (2b) \\
 & & & \sum_{j=1}^n (\lambda_j g_j + c \mu_j b_j) \geq g_d, & & & (2c) \\
 & & & \sum_{j=1}^n \lambda_j b_j = \theta_d b_d, & & & (2d) \\
 & & & \sum_{j=1}^n (\lambda_j + \mu_j) = 1, & & & (2e) \\
 & & & \lambda_j \geq 0 & \forall j \in J & & (2f) \\
 & & & \mu_j \geq 0 & \forall j \in J. & & (2g)
 \end{aligned}$$

In model (2),  $\theta_d$  represents CO<sub>2</sub> emission efficiency of DMU<sub>d</sub>. (2a)–(2b) reflects the strong disposability of inputs and desirable outputs. (2c) describes the weak disposability of undesirable outputs considering emission trading (Chu et al., 2021) [25]. (2d) is in line with the weak disposability of undesired output (Kuosmanen, 2005) [27]. (2e) means that the return to scale is considered belonging to VRS. (2f) and (2g) constrain the intensity variable  $\lambda_j$  and  $\mu_j$ . Using model (2), we can initially obtain the current emission efficiency of each DMU and analyze the differences of efficiency between DMUs.

**Remark 1.** We can easily prove that the emission efficiency  $\theta_d$  decreases when the emission permit trading price  $c$  increases. It indicates that increasing  $c$  will cause the reduction of emission efficiency  $\theta_d$ , which allows DMU to further improve its own emission reduction activities to increase efficiency.

The ZSG-DEA method is usually used to evaluate allocation result’s efficiency. The standard ZSG-DEA model is show as model (3). In model (3), the inefficient DMU<sub>d</sub> allocates the inefficient undesired output  $(1 - \theta_d)b_d$  according to the ratio  $\frac{b_d}{\sum_{j=1, j \neq d}^n b_j}$  to other DMUs, namely,  $\frac{b_d(1-h_d)}{\sum_{j=1, j \neq d}^n b_j}$  (Yang et al., 2020) [21].  $h_d$  evaluates the efficiency of DMU<sub>d</sub>. The closer value of  $h_d$  is to 1, the closer to the frontier is the DMU<sub>d</sub> and the more reasonable the carbon emission allocation result. However, this model may be inapplicable to countries that open carbon emission permit trading markets..

$$\begin{aligned}
 h_d^* = & & & & & & & \min h_d \\
 & & & \sum_{j=1}^n (\lambda_j + \mu_j) x_{ij} \leq x_{id}, & i = 1, 2, \dots, m & & (3a) \\
 & & & \sum_{j=1}^n \lambda_j y_{rj} \geq y_{rd}, & r = 1, 2, \dots, s & & (3b) \\
 & & & \sum_{j=1}^n \lambda_j g_j \geq g_d, & & & (3c) \\
 & & & \sum_{j=1}^n \lambda_j b_j [1 + \frac{b_d(1-h_d)}{\sum_{j=1, j \neq d}^n b_j}] = h_d b_d, & & & (3d)
 \end{aligned}$$

$$\sum_{j=1}^n (\lambda_j + \mu_j) = 1, \quad (3e)$$

$$\lambda_j \geq 0, \quad \forall j \in J \quad (3f)$$

$$\mu_j \geq 0 \quad \forall j \in J. \quad (3g)$$

By considering carbon emission permit trading, we want to improve the above model (3) to calculate allocation efficiency and make a reallocation of carbon emission permits referring to previous studies. So, we proposed model (4) for emission permit reallocation. In model (4), the difference from the previous one is that we consider carbon emission permit trading in the production process. So, the production possibility set compared with model (3) has some change which is mainly focused on the constraint of monetary outputs  $g$  (i.e., the third constraint).

$$h'_d = \min h'_d$$

$$\sum_{j=1}^n (\lambda_j + \mu_j) x_{ij} \leq x_{id}, \quad i = 1, 2, \dots, m \quad (4a)$$

$$\sum_{j=1}^n \lambda_j y_{rj} \geq y_{rd}, \quad r = 1, 2, \dots, s \quad (4b)$$

$$\sum_{j=1}^n (\lambda_j g_j + c \mu_j b_j) \geq g_d, \quad (4c)$$

$$\sum_{j=1}^n \lambda_j b_j \left[ 1 + \frac{b_d(1-h'_d)}{\sum_{j=1, j \neq d}^n b_j} \right] = h'_d b_d, \quad (4d)$$

$$\sum_{j=1}^n (\lambda_j + \mu_j) = 1, \quad (4e)$$

$$\lambda_j \geq 0 \quad \forall j \in J \quad (4f)$$

$$\mu_j \geq 0 \quad \forall j \in J. \quad (4g)$$

Model (4) is non-linear. We use Lins' method to connect ZSG-DEA with BCC-DEA. The frontier of ZSG is established by the frontier under the BCC model through an adjustment coefficient  $\left[ 1 + \frac{b_d(1-h'_d)}{\sum_{j=1, j \neq d}^n b_j} \right]$ .

$$\theta_d \left[ 1 + \frac{b_d(1-h'_d)}{\sum_{j=1, j \neq d}^n b_j} \right] = h'_d \quad (5)$$

Then, the ZSG efficiency can be obtained through formula (5). The improved carbon emission allocation mechanism is shown as formula (6) ( $t$  is the  $t^{th}$  adjusted allocation plan).

$$b_j^{t*} = \begin{cases} b_j^{t-1*} \left[ 1 + \frac{b_j^{t-1*}(1-h'_d{}^{t-1*})}{\sum_{j=1, j \neq d}^n b_j^{t-1*}} \right], & \text{for } j \neq d \\ \vdots \\ h'_d{}^{t-1*} b_d{}^{t-1*}, & \text{for } j = d \end{cases} \quad (6)$$

Comparing the proposed model (4) with the standard ZSG-DEA model (3), we propose some theorems and remarks as follows:

**Theorem 1.** Any feasible solution of model (3) is feasible to model (4).

**Proof.** Models (3) and (4) have the same constraint groups except for the constraints (i.e., (3c) and (4c)) built for the monetary outputs. Assuming  $(\lambda_j^*, u_j^*, h_d^*, \forall j \in J)$  to be the optimal solution of model (3). In constraint group (4c), we have  $\mu_j^* \geq 0, \forall j \in J, c \geq 0, b_j \geq 0, \forall j \in J$ . Therefore,  $(\lambda_j^*, u_j^*, h_d^*, \forall j \in J)$  is feasible to model (4). Q.E.D.

**Remark 2.** Theorem 1 indicates that the study's production possibility set is expanded with the adoption of emission permit trading. Specifically, more possible allocations of the emission permits are adopted in the new production technology.

**Proposition 1.**  $h'_d \leq h^*, \forall d \in j$ .

**Proof.** This proposition can be easily obtained according to the proof of Theorem 1, we omit it here. Q.E.D.

**Remark 3.** Proposition 1 shows that the carbon emission efficiency in the context of carbon emission permit trading is not higher than that in the case without emission permit trading. In practice, the establishment of the carbon emission permit trading allows organizations to continue to improve so as to further improve their carbon emission efficiency and positively promote their enthusiasm to reduce emissions.

**Remark 4.** The carbon emission allocation mechanism calculated in model (4) could be the quickest to achieve the organization's emission reduction goals. Given that the target emission  $h'_d b_d$  of the  $DMU_d$  in this model is less than or equal to the target result in the model (3), the emission reduction responsibility of any DMU will increase, jointly promoting the emission reduction of all DMUs and expediting the realization of the total emission reduction target.

**Theorem 2.**  $h'_d$  of model (4) is monotonic increasing with the increasing of  $\theta_d$  of model(2).

**Proof.** By model (5), it is not difficult to find that  $h'_d$  has a functional relationship with  $\theta_d$ . Model (5) is equivalent to  $h'_d = \frac{\theta_d \sum b_j}{\sum_{j=1, j \neq d}^n b_j + \theta_d b_d}$ . When  $\theta_d > 0$ ,  $h'_d$  is increasing with the increment of  $\theta_d$ . Q.E.D.

**Theorem 3.** When the value of ZSG-DEA efficiency  $h'_d$  is regarded as a function of the carbon emission trading price  $c$ ,  $h'_d$  monotonously does not increase as  $c$  increases.

**Proof.** Let  $0 < c^1 \leq c^2$ . Assume the optimal solution of model (4) is  $(\lambda_j^{1*}, \forall j \in J, \mu_j^{1*}, \forall j \in J, h'_d^{1*})$  when  $c = c^1$ . We can obtain  $\sum_{j=1}^n (\lambda_j^{1*} g_j + c^1 \mu_j^{1*} b_j) \geq g_d$  due to the constraint (4c) and  $\sum_{j=1}^n (\lambda_j^{1*} g_j + c^2 \mu_j^{1*} b_j) \geq g_d$  because  $c^2 \geq c^1 > 0$ ,  $\mu_j^{1*} \geq 0, \forall j \in J$ , and  $b_j \geq 0, \forall j \in J$ . Therefore, the solution  $(\lambda_j^{1*}, \forall j \in J, \mu_j^{1*}, \forall j \in J, h'_d^{1*})$  satisfies all the constraints and is also feasible to model (4) when  $c = c^2$ . Therefore,  $h'_d(c^2) \leq h'_d(c^1) = h'_d^{1*}$ . Q.E.D.

## Data sources

### Data of inputs and outputs in 2013-2017

This article first considers the performance evaluation of organizations that produce carbon dioxide. At the beginning of the carbon emission permit trading pilots, fire power generation was included in the list of key controls to limit carbon dioxide emissions. The fire power industry is currently considered a high-emission, high-energy-consumption, and low-efficiency industry. Therefore, this article selects China's fire power industry as the research object. The total energy consumption (unit: 10 thousand tons /tce), labor force (unit: 10 thousand persons), and installed capacity (unit: 10 thousand kw) are selected as inputs in the production process of the fire power industry. Lee et al. (2018) [28] and Ma et al. (2018) [29] also used this type of indicator as inputs. Those data mainly come from the National Bureau of Statistics of China(NBS), China Statistical Yearbook 2014–2018, and China Electricity Yearbook 2014–2018. The desirable output is fire power generation (unit:100 million kW-h) whose data come from the NBS. The monetary output is the obtained environmental protection governance fund for air pollution(unit: million yuan), and the undesired output is the emission level of carbon dioxide (unit:10 thousand tons), which is calculated through the method proposed by IPCC 2006. Considering that no statistics exist on the total energy consumption (coal, oil, natural gas) and regional consumption in 2018, we select the data from 2013 to 2017 to evaluate the carbon emission efficiency of each region during this period. The corresponding carbon emission permit trading price in all regions of the country is unified because of the collecting its inconvenience in various regions each year. The unified price in each year comes from the average value of each region of CSMAR each year, as shown in Table 1.

Regarding the monetary output, the funds collected on the State Council of the People's Republic of China's website for air pollution prevention and control during 2013–2017 were 5, 9.8, 10.6, 11.2 and 20 billion, respectively. Here, we will obtain the monetary output of each region by multiplying the proportion of fixed asset investment in the fire power industry by the annual air pollution prevention and control funds. Table 2 shows the descriptive statistics from 2013 to 2017. In this study, MATLAB R2018a is used for programming operations.

Year	2013	2014	2015	2016	2017
Average price	66.854	43.691	31.329	27.097	24.995

**Table 1:** The carbon emission permit trading price in 2013-2017 (unit: yuan/ton)

Year		Energy consumption	Installed capacity	Labor force	Electricity generation	Monetary revenue	Carbon emission
2013	Mean	3672.93	2898.03	13.63	1417.45	172.41	6389.13
	S.D.	2640.27	2115.73	7.37	1082.30	91.99	4663.78
	Min.	314.73	235.00	1.85	134.43	29.18	447.37
	Max.	9509.50	7555.00	32.18	4099.24	382.62	16703.65
2014	Mean	3398.37	3082.86	13.56	1399.11	337.93	5897.48
	S.D.	2505.75	2256.30	7.20	1099.99	195.21	4426.80
	Min.	295.77	242.00	1.89	129.86	66.01	419.13
	Max.	9273.31	8073.00	30.80	4049.84	892.60	16278.23
2015	Mean	3183.22	3321.24	13.31	1391.70	365.52	5471.57
	S.D.	2408.77	2440.94	7.14	1175.34	215.04	4247.99
	Min.	308.17	318.00	1.96	122.00	49.58	416.92
	Max.	9100.82	8754.00	30.71	4502.09	783.95	15912.01
2016	Mean	3301.28	3492.38	13.01	1453.43	386.21	5650.83
	S.D.	2493.62	2558.31	7.01	1278.72	256.90	4390.93
	Min.	302.18	402.00	2.16	152.19	44.43	342.75
	Max.	9485.61	9540.00	31.27	5142.88	1085.83	16525.78
2017	Mean	3556.13	3629.17	12.61	1526.10	689.66	6067.16
	S.D.	2729.79	2704.85	6.97	1313.17	492.08	4794.49
	Min.	340.12	399.00	2.15	161.19	77.21	208.64
	Max.	10399.92	10335.00	29.92	4913.85	2264.74	18212.63

**Table 2:** Descriptive statistics of the raw data

## Prediction of carbon emission levels in 2030

The main forecasting method used in this study is the autoregressive integrated moving average model. We use the data from 1997 to 2017 to predict the input–output data in 2030. For the missing value data, this article uses the average value of the adjacent five years to fill in. For the input index, the data on the labor force, energy consumption, and installed capacity come from the NBS, China Energy Statistical Yearbook, and China Electric Power Yearbook, respectively.

For the output index, electricity generation data come from Power Industry Statistical Data Collection (1998–2018). For the monetary output, since the “12th Five-Year Plan” period, the gross domestic production (GDP) has developed slowly with an annual growth rate ( $\alpha$ ) of approximately 6%. Environmental protection funds come from a certain percentage ( $c_1$ ) of GDP and environmental protection funds for air pollution come from another certain percentage ( $c_2$ ) of environmental protection funds. About  $c_1$ , according to the experience of developed countries, when the proportion of environmental protection investment in GDP is in the range of 1%–1.5%, the deterioration of environmental pollution may be curbed. When the proportion reaches 2%–3%, the environmental quality may be improved (Wan L and Du, 2021; Cai and Song, 2011) [30,31]. The proportion of environmental protection investment

in 2011–2020 is generally 1%–1.9% in China. Therefore, in response to the national goal of "lucid waters and lush mountains", we assume that  $c_1$  is at least 2% of the GDP that year. About  $c_2$ , We assume it in 2030 is approximately 6%.

In 2015, the Chinese GDP was 68885.82 billion yuan (from NBS). Then, through formula (7) we obtain the environmental protection fund for air pollution, which is 200 billion yuan. Then, we use fixed assets in 2030 as the allocation ratio of monetary output among provinces in 2030.

$$GDP_t = GDP_{2015} * (1 + \alpha)^{t-2015}$$

$$g_t = GDP_t * c_1 * c_2$$
(7)

For the carbon dioxide index, the target of carbon emission intensity in 2030 will be reduced by 60%–65% compared with that in 2005. We select 65% as the emission reduction target, that is, the carbon emission intensity in 2030, is 35% of that in 2005. We can obtain the total carbon emissions in 2030 by formula(7) and (8).

$$\frac{CO_{22030}}{GDP_{2030}} = \frac{CO_{22005}}{GDP_{2005}} * 35\%$$
(8)

According to China emission accounts and datasets and the NBS, the carbon dioxide emission in 2005 is 5401.1 million tons, and the GDP that year is 18731.89 billion yuan. Therefore, through formula (8), the total carbon dioxide emission in 2030 will be 16,660.44 million tons. According to statistics, the carbon dioxide emitted by China’s fire power industry in 2019 exceeds 40% of the national carbon dioxide. Considering the progress of emission reduction technology and the government’s attention to emission reduction in 2020–2030, this article assumes that the carbon dioxide emitted by the fire power industry in 2030 will account for approximately 20% of the total carbon dioxide, that is, 3332.088 million tons (Table 3).

	Labor force (10 <sup>4</sup> person)	Installed capacity (10 <sup>4</sup> kw)	Energy consumption (10 <sup>4</sup> tons /tce)	Electricity generation (10 <sup>8</sup> kw)	Electricity sales revenue (10 <sup>6</sup> yuan)	Carbon emission (10 <sup>4</sup> tons)
Mean	14.66	5556.51	7424.45	2121.75	6896.55	11489.96
S.D.	8.37	4246.72	5816.52	1880.16	5052.88	1928.96
Min.	2.01	526.55	991.50	235.91	749.75	7721.60
Max.	38.11	15954.02	22846.86	7570.42	22677.65	14981.73
Sum	425.02	161138.9	215309	61530.62	200000	333208.8

Table 3: Descriptive statistics analysis in 2030

### Empirical analyses

In this section, we first study the emission status of China's fire power generation industry in section 4.1. Then section 4.2 considers the principle of fairness and efficiency and proposes a new carbon emission allocation plan (by model (3) and model (4)) which can achieve the carbon emission target in 2030.

### Carbon emission performance considering carbon emission permit trading in 2013–2017

Table 1 shows the carbon emission permit trading prices for 2013–2017. Through model (2), we obtain the BCC efficiency of each region considering carbon emission permit trading (Table 4 and Figure 1).



Regions	2013	2014	2015	2016	2017
Beijing	0.8656	1	1	1	1
Tianjin	0.8764	0.7098	0.8520	0.8199	0.8706
Hebei	0.6083	0.6524	1	1	1
Shanxi	0.4759	0.4568	0.4021	0.3905	0.3338
Inner Mongolia	1	1	1	0.5706	0.5633
Liaoning	0.4185	0.4401	0.4357	0.4291	0.3936
Jilin	0.3231	0.3216	0.2242	0.2045	0.2158
Heilongjiang	0.3090	0.3125	0.2526	0.2250	0.2030
Shanghai	1	1	1	1	1
Jiangsu	1	1	1	1	1
Zhejiang	1	1	1	1	1
Anhui	0.8173	0.7913	0.7907	0.8106	0.8448
Fujian	0.9035	1	0.8511	1	1
Jiangxi	0.5907	0.5558	0.5102	0.6487	1
Shandong	0.5851	0.5671	1	1	1
Henan	0.6587	0.6444	0.5992	0.6163	0.6273
Hubei	0.4747	0.4317	0.3913	0.3931	0.4037
Hunan	0.4217	0.3726	0.2673	0.2377	0.2323
Guangdong	1	1	1	1	1
Guangxi	0.6366	0.5181	0.3096	0.2882	0.2965
Hainan	1	1	1	1	1
Chongqing	0.5006	0.3659	0.2897	0.3125	0.3057
Sichuan	0.2993	0.3431	0.2496	0.1984	1
Guizhou	0.5028	0.4442	0.3720	0.3889	0.4094
Yunnan	0.2689	0.2272	0.0980	0.0648	0.0439
Shaanxi	1	1	0.5984	0.7369	0.7061
Gansu	0.6328	0.6024	0.4989	0.4097	0.3804
Qinghai	1	1	1	1	1
Ningxia	1	1	1	1	1

Table 4: Efficiency evaluation results considering TRD during 2013 and 2017

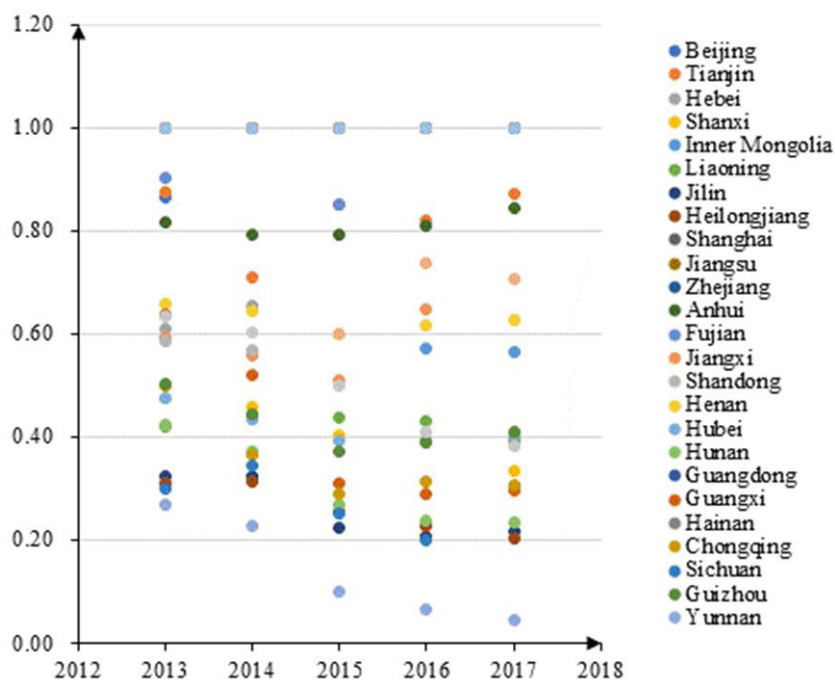


Figure 1: Efficiency evaluation results considering TRD

Table 4 shows that Shanghai, Jiangsu, Zhejiang, Guangdong, Hainan, Qinghai, and Ningxia are always efficient. Most of them belong to the southeast coastal area. Only Qinghai and Ningxia are in the northwest. The former has rapid economic development, advanced technology and pollution control equipment, which may keep the province efficient. In addition, the geographical advantages of the coastal areas make them mainly develop the tertiary industry. However, Qinghai and Ningxia are sparsely populated and rich in tourism resources. They mainly develop tourism, so the industry produces less carbon dioxide.

For inefficient areas, the efficiency of most areas is generally between 0.3 and 0.6, such as Shanxi, Liaoning, Hubei, Chongqing, and Guizhou. The efficiency in some areas has significant changes. For example, Inner Mongolia and Shaanxi changed from efficient to inefficient; Beijing, Hebei, Jiangxi, Sichuan, and Shandong changed from inefficient to efficient. In addition, some areas changed from inefficient to efficient and then to inefficient, such as Fujian. Figure 1 also depicts that the efficiency difference among regions is large, and the difference was the largest in 2017. The number of efficient regions in 2017 was greater than that in 2013, but the average efficiency in 2017 was lower. The reason may be the full launch of the carbon emission permit trading in 2017, which results in the DMUs who newly participate in the market need to adjust the industrial structure. In addition, we noticed that the carbon emission permit trading price from 2013 to 2017 was different and showed a downward trend. Given that the input–output level is always changed, we hardly find the concrete impact of carbon emission permit trading prices on efficiency changes. Therefore, we select inputs and outputs in 2017 to conduct sensitivity analysis of carbon emission permit trading price in next section 5.1.

### Allocating carbon dioxide emission permits in 2030

Regarding the initial carbon emission situation of the fire power industry in 2030, this study first considers the carbon dioxide emissions of each region based on the principle of fairness referring to the comprehensive index method of Zhang et al. (2017) [23]. The carbon dioxide emissions from 2013 to 2017 and the per capita environmental protection fund for air pollution are selected to represent the region's emission reduction responsibility and emission reduction potential, respectively. The initial allocation is obtained through information entropy method referring to Cui et al. (2021) [32], Han Y et al.(2018) [33] and Yang et al. (2020) [21]. See Appendix for the calculation process of information entropy method. According to the information entropy method and 2030 carbon dioxide emission permit target, the result of the allocation in each region is obtained as Table 5 and Figure 2. The last column of Table 3 presents the descriptive statistics consisting of the initial allocation results.

Assuming that the carbon emission permit trading price in 2030 is 100 yuan/ton, model (2) proposed in Section 2 is used to measure the efficiency of DMU in the context of carbon emission permit trading in 2030. The third column of Table 5 shows the results. First, 13 DMUs have an efficiency value of 1, namely, Tianjin, Hebei, Inner Mongolia, Shanghai, Zhejiang, Anhui, Shandong, Jiangxi, Guangdong, Sichuan, Hainan, Ningxia, and Qinghai. Among these efficient DMUs, they are mainly distributed in the southeast coastal areas, and mainly belong to some developed areas. On the one hand, the southeast coast has less fossil energy available due to its geographical advantages. What these regions develop is mainly the tertiary industry. On the other hand, the technology in developed areas is more advanced, so the emission efficiency of fire power generation is high and the carbon dioxide emissions are relatively low. Therefore, the efficiency in the above regions is higher. However, we found that some regions have very low efficiency values, such as Jiangsu, which have efficiencies of 0.163. Jiangsu has quick economic development and owns relatively advanced technology. Moreover, in 2013–2017, Jiangsu is keeping efficient with an efficiency of 1. Hence, the efficiency after only considering the principle of fairness may not be very suitable. Then, we consider the efficiency principle by the improved ZSG-DEA model (4) to adjust the initial allocation results.

The fourth to sixth columns in Table 5 show the ZSG efficiency obtained by using model (4) and the results went through one iteration and three iterations, respectively. Compared with the third column of Table 5, for inefficient DMUs, the initial efficiency of ZSG is slightly higher than that of BCC. For example, the efficiency of BCC in Beijing is 0.626, and that of ZSG is 0.631. After one iteration, the efficiency of ZSG is evidently higher than that of BCC. The efficiency in Beijing becomes 0.978. However, the efficiency in Sichuan is still very low, so we continue to iterate. The final result is that all DMUs become efficient. The last two columns in Table 5 present the allocation results adjusted by the ZSG-DEA model and the adjustment level in each region. Inefficient regions will

become efficient after reducing their carbon emission level to efficient regions. For example, Shanxi is rich in coal resources, which produces a relatively large amount of carbon emissions. Moreover, its regional development speed is not quick, so the efficiency of carbon emission in Shanxi is low. After adjustment of allocation plan by ZSG-DEA model (4), its efficient carbon emissions in 2030 should be 180 million tons. The adjustment results show that the carbon emissions allocated by inefficient DMUs should be less than initial allocation. This conclusion is also close to reality, which promotes the emission reduction in areas with high carbon dioxide emissions and low efficiency in reality to achieve the carbon peak target in 2030.

Regions	Initial allocation results	BCC efficiency	ZSG efficiency	1 <sup>st</sup> iteration	3 <sup>rd</sup> iteration	ZSG allocation results	Adjustment level
Beijing	7560.78	0.626	0.631	0.978	1.000	7538.12	-22.66
Tianjin	7144.71	1.000	1.000	1.000	1.000	11666.22	4521.51
Hebei	17074.11	1.000	1.000	1.000	1.000	27879.40	10805.29
Shanxi	20565.30	0.539	0.555	1.000	1.000	18088.48	-2476.83
Inner Mongolia	18792.80	1.000	1.000	1.000	1.000	30685.75	11892.95
Liaoning	14333.33	0.369	0.379	1.000	1.000	8625.72	-5707.61
Jilin	11005.88	0.204	0.210	1.000	1.000	3672.39	-7333.49
Heilongjiang	13406.04	0.199	0.206	1.000	1.000	4354.96	-9051.09
Shanghai	8998.41	1.000	1.000	1.000	1.000	14693.02	5694.61
Jiangsu	16219.63	0.163	0.171	0.988	1.000	4250.80	-11968.83
Zhejiang	10903.78	1.000	1.000	1.000	1.000	17804.20	6900.42
Anhui	11714.60	1.000	1.000	1.000	1.000	19128.13	7413.53
Fujian	7403.07	0.621	0.627	0.991	1.000	7430.35	27.28
Jiangxi	9591.45	1.000	1.000	1.000	1.000	15661.37	6069.91
Shandong	21277.96	1.000	1.000	1.000	1.000	34743.63	13465.67
Henan	16330.43	0.619	0.634	0.996	1.000	16436.78	106.36
Hubei	11655.75	0.373	0.383	0.985	1.000	6978.62	-4677.13
Hunan	11690.92	0.268	0.277	0.982	1.000	5022.35	-6668.58
Guangdong	13923.20	1.000	1.000	1.000	1.000	22734.44	8811.24
Guangxi	8945.85	0.272	0.279	0.992	1.000	3927.64	-5018.21
Hainan	6900.46	1.000	1.000	1.000	1.000	11267.39	4366.93
Chongqing	8512.14	0.190	0.196	1.000	1.000	2646.87	-5865.27
Sichuan	10037.64	1.000	1.000	0.144	1.000	2238.05	-7799.59
Guizhou	12771.26	0.362	0.375	1.000	1.000	7558.34	-5212.92
Yunnan	8294.92	0.134	0.139	0.998	1.000	1817.58	-6477.33
Shaanxi	13253.06	0.568	0.583	1.000	1.000	12292.19	-960.88
Gansu	8936.71	0.297	0.305	1.000	1.000	4326.68	-4610.03
Qinghai	328.11	1.000	1.000	1.000	1.000	535.75	207.64
Ningxia	5636.49	1.000	1.000	1.000	1.000	9203.52	3567.03

**Table 5:** Results of efficiency and allocation.(unit:10<sup>4</sup> tons)

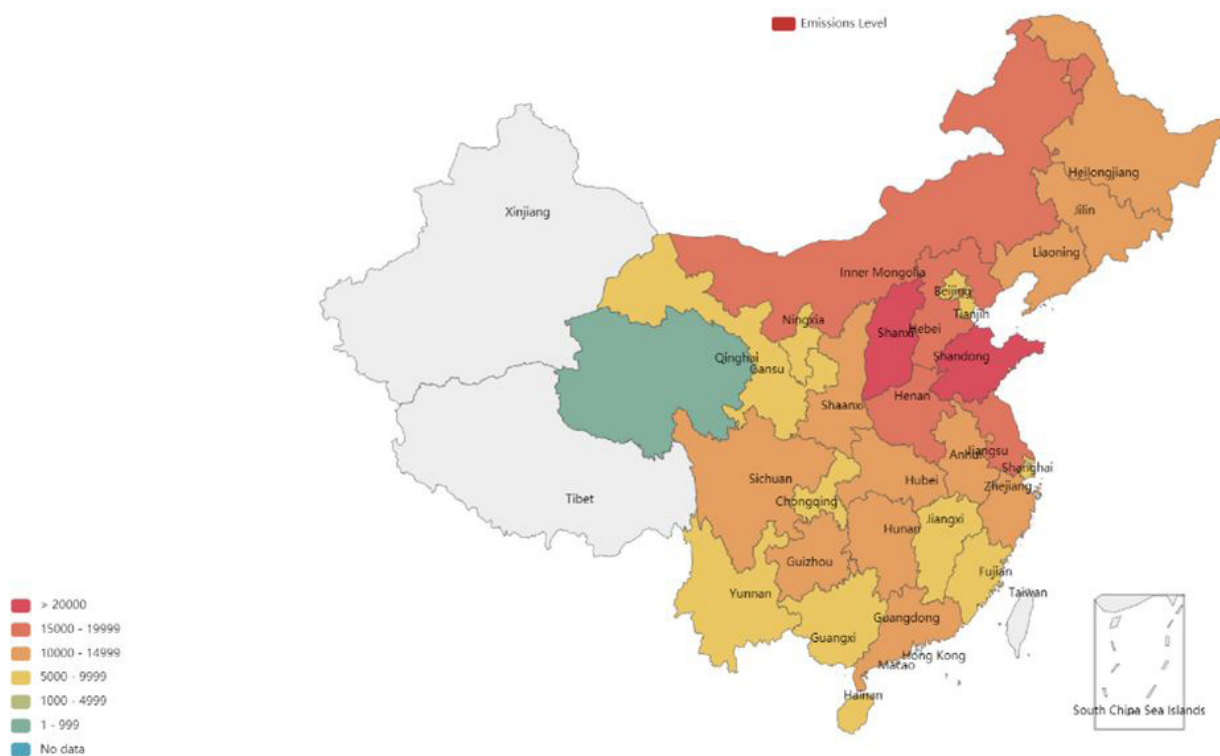


Figure 2: Initial allocation level of carbon emission permit only considering fairness principle

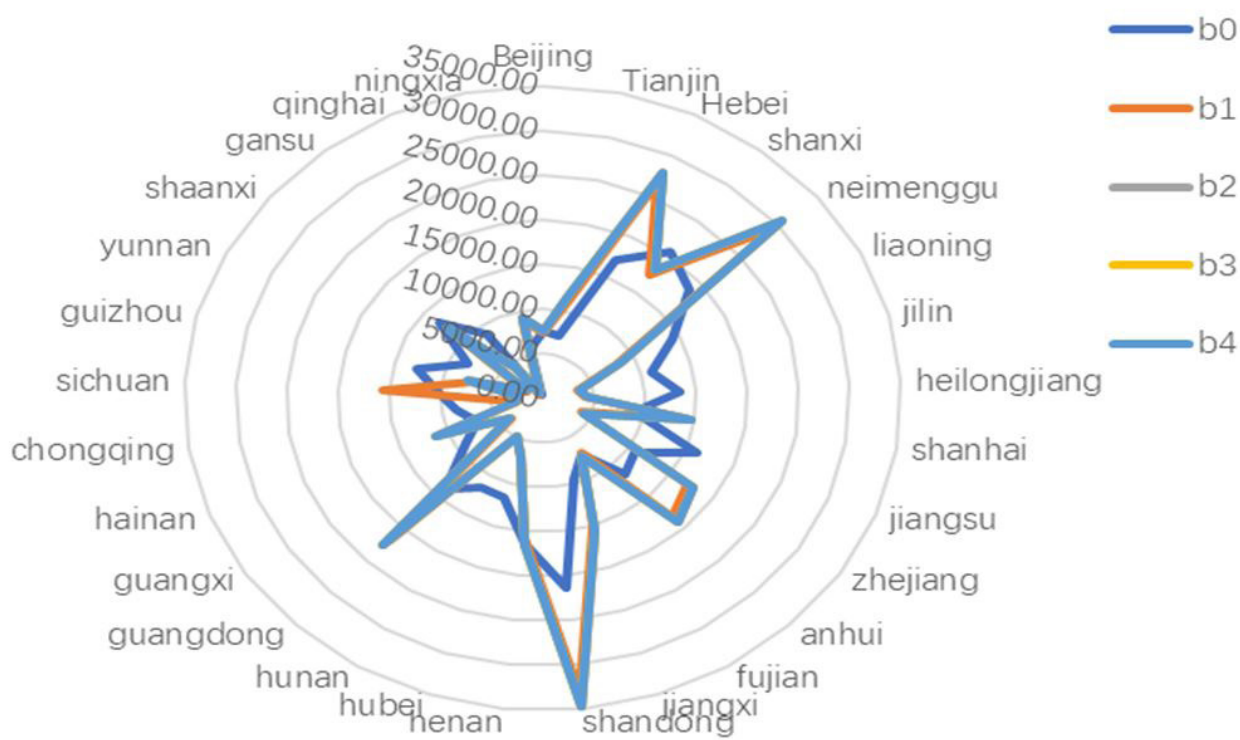


Figure 3: Results of iterative process of initial allocation considering carbon emission permit trading in 2030

In Figure 3, b0 is the initial allocation plan considering the principle of fairness. b1–b3 are the results of the intermediate iterations in each region, and b4 is the final allocation plan obtained on the basis of the principle of fairness that all regions are efficient. b0 is relatively uniform. Considering the existence of regional heterogeneity, the final allocation result should be as shown in b4. For example, Shanxi takes 1.6% of the country’s land area and consumes approximately 10% of the country’s coal, which has a heavy responsibility for reducing emissions. After the adjustment of the ZSG-DEA model, its efficient 2030 carbon emissions should be 180 million tons. This case requires Shanxi to learn advanced technologies from developed regions such as Shanghai and Guangdong, to improve carbon emission. Moreover, Shanxi should speed up the transformation and increase the promotion of new energy power generation. In addition, the last column of Table 5 shows that more than half of the regions need to do abatement, which also shows that China’s carbon emission reduction still needs to continue to improve.

### Sensitivity analysis and comparison

Section 5.1 makes a sensitivity analysis of carbon emissions permit trading prices based on section 4.1. section 5.2 highlights the impact of carbon emissions permit trading on carbon emissions allocation.

### Sensitivity analysis of carbon emission permit trading price on efficiency changes

First, we take the carbon emission permit trading price in the range of 1–100 with a step of 10. Then, we use the fire power industry data in 2017 to make a sensitivity analysis and get Figure 4.

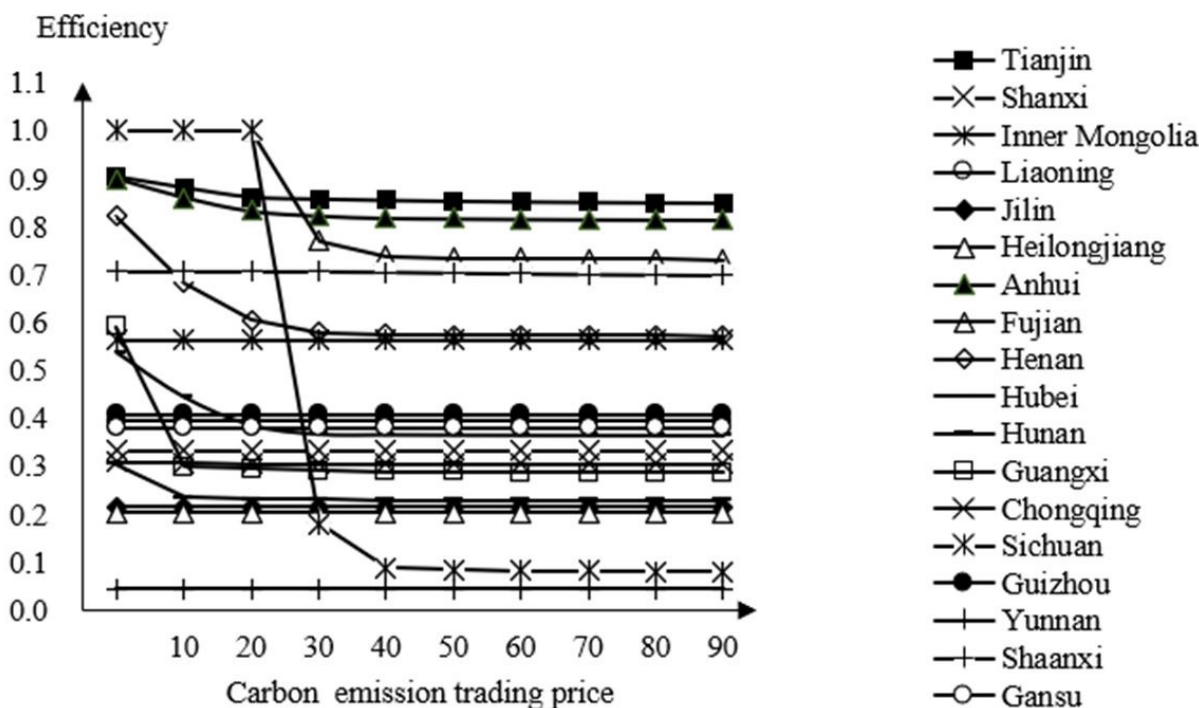


Figure 4: Impact of different carbon emission permit trading prices on inefficient DMU

Figure 4 shows the following points: First, as the carbon emission permit trading price increases, the overall efficiency shows a downward trend, indicating that the price will affect the efficiency. Moreover, the decreasing trend of efficiencies of DMUs are not the same. For example, when the carbon emission permit trading price of Sichuan is approximately 30, as the carbon emission permit trading price continues to increase, its efficiency value suddenly drops from 1 to 0.2. However, this case cannot be observed in Tianjin. This finding shows that the sensitivity of different DMUs to carbon emission permit trading prices is different. Second, the specific range of carbon emissions trading price changes can significantly affect the efficiency of DMU. For example, when the carbon emission permit trading price ranges from 30 to 50 yuan/ton, the efficiency of Fujian and Sichuan changes significantly. However, the corresponding carbon emission permit trading price in Henan ranges from 10 to 30 yuan/ton that causes the significant efficiency change of Henan. The conclusion is in line with the limited enhancement property proposed in Chu et al.(2021) [25]. Finally, as the carbon emission permit trading price increases, the efficiency of some DMUs does not change.

Among these DMUs, the efficiency of 11 efficient DMUs does not change, which is not shown in Figure 4. They are Beijing, Hebei, Shanghai, Jiangsu, Zhejiang, Guangdong, Jiangxi, Shandong, Hainan, Qinghai, and Ningxia. The reason may be that the carbon emission permit trading price needs to be greater than 100 when the efficiency value of these DMUs changes.

For inefficient DMUs, the efficiency of Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Guizhou, Yunnan, Gansu, and Shaanxi remained unchanged. The above-mentioned regions are mainly distributed in the northeast and remote west areas. They are only suitable for lower carbon emission permit trading prices due to current lagging regional development. Treating the above inefficient areas, improving the technology, and upgrading the equipment will help implement the carbon emission reduction plan. In addition, Figure 4 indicates that carbon emission permit trading prices have an overall impact on efficiency within 100 yuan/ton, indicating that the increasing carbon emission permit trading price is not better. The Chinese government should adopt a "differentiated treatment" policy and comprehensively consider local development conditions to reasonably set the carbon emission permit trading price.

### Considering the impact of the carbon emission permit trading on the initial allocation results

The third and fifth columns of Table 6 show the initial allocation efficiency and final allocation plan considering carbon emission permit trading. The fourth and last columns present the initial allocation efficiency and final allocation improvement plan without considering carbon emission permit trading. Two points can be easily found: First, comparing efficiency, the initial allocation efficiency considering carbon emission permit trading is relatively low. Second, in the context of carbon emission permit trading, all DMUs can continue to improve its efficiency. Moreover, the carbon allocation improvement plan considering carbon emission permit trading is different from that neglecting carbon emission permit trading.

Regions	Initial allocation results	ZSG efficiency TRD	ZSG efficiency NTRD	Final allocation plan TRD	Final allocation plan NTRD
Beijing	7560.78	0.631	1.000	7538.12	10664.01
Tianjin	7144.71	1.000	1.000	11666.22	10077.17
Hebei	17074.11	1.000	1.000	27879.40	24081.96
Shanxi	20565.30	0.555	0.554	18088.48	15624.66
Inner Mongolia	18792.80	1.000	1.000	30685.75	26506.07
Liaoning	14333.33	0.379	0.379	8625.72	7450.82
Jilin	11005.88	0.210	0.211	3672.39	3182.48
Heilongjiang	13406.04	0.206	0.206	4354.96	3761.77
Shanghai	8998.41	1.000	1.000	14693.02	12691.69
Jiangsu	16219.63	0.171	0.569	4250.80	12694.80
Zhejiang	10903.78	1.000	1.000	17804.20	15379.10
Anhui	11714.59	1.000	1.000	19128.13	16522.70

Regions	Initial allocation results	ZSG efficiency TRD	ZSG efficiency NTRD	Final allocation plan TRD	Final allocation plan NTRD
Fujian	7403.07	0.627	1.000	7430.35	10441.57
Jiangxi	9591.45	1.000	1.000	15661.37	13528.14
Shandong	21277.96	1.000	1.000	34743.63	30011.23
Henan	16330.43	0.634	0.710	16436.78	16078.17
Hubei	11655.75	0.383	0.671	6978.62	10873.12
Hunan	11690.92	0.277	0.567	5022.35	9178.91
Guangdong	13923.20	1.000	1.000	22734.44	19637.80
Guangxi	8945.85	0.279	0.508	3927.64	6306.03
Hainan	6900.46	1.000	1.000	11267.39	9732.67
Chongqing	8512.14	0.196	0.195	2646.87	2286.35
Sichuan	10037.64	1.000	1.000	2238.05	14157.46
Guizhou	12771.26	0.375	0.374	7558.34	6528.83
Yunnan	8294.92	0.139	0.267	1817.58	3043.37
Shaanxi	13253.06	0.583	0.581	12292.19	10617.88
Gansu	8936.71	0.305	0.304	4326.68	3737.35
Qinghai	328.11	1.000	1.000	535.75	462.78
Ningxia	5636.49	1.000	1.000	9203.52	7949.92

**Table 6:** Allocation improvement results under different models (unit:10<sup>4</sup> tons)

In the initial allocation, the carbon emissions of Shandong and Shanxi are more than 200 million tons and the ZSG efficiency is low (second column of Table 5). Then, we consider the efficiency principle and use model (4) to improve the initial allocation plan. Figures 5 and 6 depict the allocation results. We can find that introducing carbon emission permit trading, Guangdong is added to original two regions (Inner Mongolia and Hebei) belong to regions with the highest emission levels at the beginning (with no emission permit trading). Considering carbon emission permit trading, emissions permit in many regions (comparing green regions between Figure 5 and 6) are severely reduced, that is, more regions have greater responsibility for reducing emissions like Sichuan, Heilongjiang, and Guangxi. Therefore, we can think that the allocation considering carbon emission permit trading has made DMU's emission abatement responsibilities greater, which will urge regions to reduce emissions. Moreover, the allocation will enable the overall emission reduction target to be achieved as soon as possible.

The policy recommendations proposed are as follows: First, the development of China's southeast coastal areas is better than that of the west and northeast areas. To achieve the carbon emission abatement target in 2030, the government should make the western and northeastern regions as key emission abatement targets, limit the emission levels in the above regions and help them introduce advanced equipment and production technology of emission abatement. Second, the carbon emission permit trading price may play a role in carbon emission abatement. Thus, the price of the local carbon emission permit trading should be formulated by the local government in combination with the local development conditions and reported to the State Council of China for evaluation and audit by professional team. Third, after the allocation of carbon emission permits which considers the principles of fairness and efficiency, the government should impose greater responsibility for reducing emissions on areas with high emission and low efficiency, which is also in line with the principle of "who pollutes, who treats".

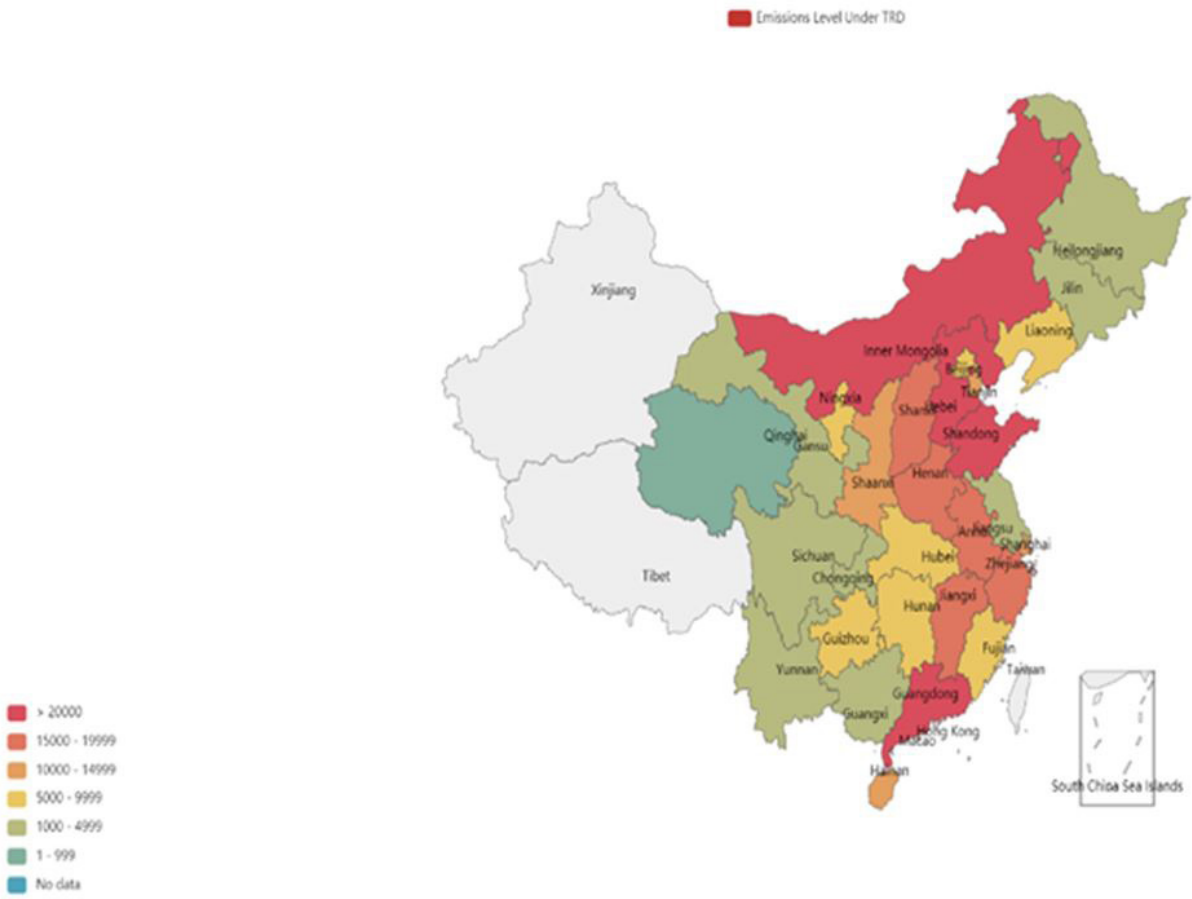


Figure 5: Allocation improvement results considering carbon emission permit trading

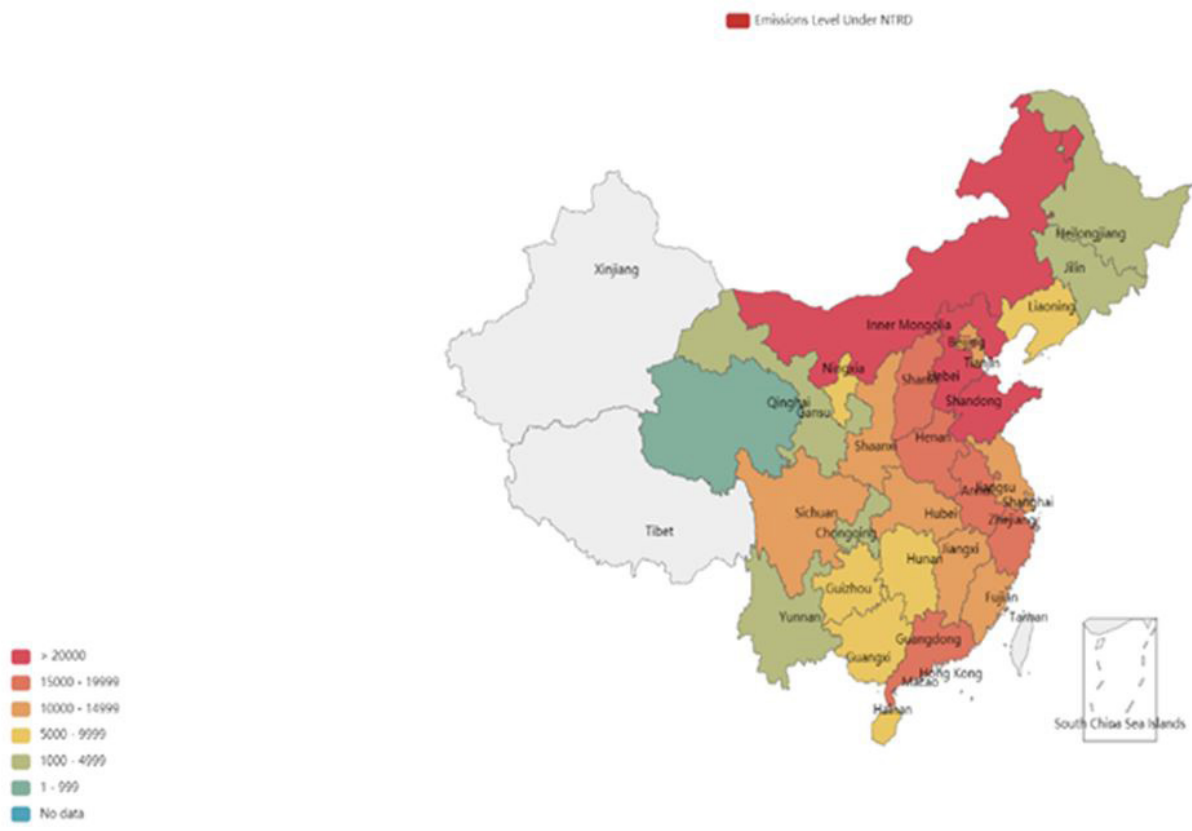


Figure 6: Allocation improvement results without considering carbon emission permit trading



## Conclusions

This paper mainly investigates the allocation mechanism of carbon emission permit considering carbon emission permit trading combining ZSG-DEA. Moreover, the study applies the ZSG-DEA model considering carbon emission permit trading to the Chinese fire power industry to evaluate their operation performance from 2013 to 2017. Then, we consider a pre-allocation plan to achieve China's carbon emission reduction targets in 2030. The information entropy method is introduced, and the allocation plan of carbon emission permits considering fairness principle is considered. After considering the efficiency principle, we improve the initial allocation results. In Section 5, we also conducted a sensitivity analysis of carbon emission permit trading prices and made the comparison of allocation results considering carbon emission permit trading and neglecting the carbon emission permit trading.

The main conclusions are as follows: First, considering carbon emission permit trading, the fire power industry in the southeast coastal area has developed well. Such development may be due to its industrial structure and geographical advantages, which may result in sufficient economic strength to introduce advanced technologies to the local fire power industry. Second, different regions have different economic development statuses, their sensitivity to carbon emission permit trading prices is also different. The local government should combine the local economic development and geographic location to formulate a suitable carbon emission permit trading price. The most important point is that under the background of carbon emission permit trading, the allocation of carbon dioxide emissions in the fire power industry in 2030 should comply with the principle of giving less emission permits to inefficient regions. That is, the carbon emission level of inefficient organization should be limited and given greater responsibility for emission reduction. This finding urges each inefficient region to strive to reduce emissions through technological improvement or industrial transformation [34-38].

## Conclusion

This study may have some future research directions, for example, the study of gradual carbon emission reduction plans considering carbon emission permit trading. This article predicts and adjusts the allocation of carbon emission permits for the fire power industry in 2030. For each region, how to achieve the predicted carbon emission permits within 10 years is worth to study. This further research could provide production management advice for high-emission and low-efficiency industries, such as the fire power industry.

## Acknowledgements

The authors appreciate the publication of this article by the funding support from the National Natural Science Foundation of China (No. 71901225) and the Natural Science Foundation of Hunan Province (No. 2020JJ5778).

1. Tanpaifang (2020) China's carbon emissions trading network, China.
2. Zhang Z, Pan SY, Li H, Cai J, Olabi AG, et al. (2020) Recent advances in carbon dioxide utilization. *Renew Sust Energ Rev* 125: 109799.
3. Wang H, Zhang Y, Lu X, Nielsen CP, Bi J (2015) Understanding China's carbon dioxide emissions from both production and consumption perspectives. *Renew Sust Energ Rev* 52: 189-200.
4. Lee CY (2019) Decentralized allocation of emission permits by Nash data envelopment analysis in the coal-fired power market. *J Environ Manage* 241: 353-62.
5. Wang R, Wang Q, Yao S (2021) Evaluation and difference analysis of regional energy efficiency in China under the carbon neutrality targets: Insights from DEA and Theil models. *J Environ Manage* 293: 112958.
6. Dai H, Xie Y, Liu J, Masui T (2018) Aligning renewable energy targets with carbon emissions trading to achieve China's INDCs: A general equilibrium assessment. *Renew Sust Energ Rev* 82: 4121-31.
7. Goulder LH, Parry IW, Williams Iii RC, Burtraw D (1999) The cost-efficiency of alternative instruments for environmental protection in a second-best setting. *J Public Econ* 72: 329-60.
8. Fischer C, Fox AK (2004) Output-based allocations of emissions permits: efficiency and distributional effects in a general equilibrium setting with taxes and trade (No. 1318-2016-103313) 10.22004/ag.econ.10654.
9. Takeda S, Arimura TH, Tamechika H, Fischer C, Fox AK (2014) Output-based allocation of emissions permits for mitigating the leakage and competitiveness issues for the Japanese economy. *Environ Econ Policy Stud* 16: 89-110.
10. Momeni E, Lotfi FH, Saen RF, Najafi E (2019) Centralized DEA-based reallocation of emission permits under cap and trade regulation. *J Cleaner Prod* 234: 306-14.
11. Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision making units. *Eur J Oper Res* 2: 429-44.
12. Lozano S, Villa G, Brännlund R (2009) Centralised reallocation of emission permits using DEA. *Eur J Oper Res* 193: 752-60.
13. Sun J, Wu J, Liang L, Zhong RY, Huang GQ (2014) Allocation of emission permits using DEA: Centralised and individual points of view. *Int J Prod Res* 52: 419-35.
14. Feng C, Chu F, Ding J, Bi G, Liang L (2015) Carbon emissions abatement (CEA) allocation and compensation schemes based on DEA. *Omega-Int J Manage Sci* 53: 78-89.
15. Wu J, Chu JF, Liang L (2016) Target setting and allocation of carbon emissions abatement based on DEA and closest target: an application to 20 APEC economies. *Nat Hazards* 84: 279-96.
16. Yu A, You J, Rudkin S, Zhang H (2019) Industrial carbon abatement allocations and regional collaboration: Re-evaluating China through a modified data envelopment analysis. *Appl Energy* 233: 232-43.
17. Du J, Pan M, Chen Y, Duan Y (2020) An efficiency-based allocation of carbon emissions allowance: a case study in China. *J Cleaner Prod* 251: 119346.
18. Lins MPE, Gomes EG, de Mello JCCS, de Mello AJRS (2003) Olympic ranking based on a zero sum gains DEA model. *Eur J Oper Res* 148: 312-22.

19. Gomes EG, Lins MPE (2008) Modelling undesirable outputs with zero sum gains data envelopment analysis models. *J Oper Res Soc* 59: 616-23.
20. Lin T, Ning JF (2011) Study on allocation efficiency of carbon emission permit in EU ETS based on ZSG-DEA model. *The Journal of Quantitative & Technical Economics* 3: 36-50.
21. Yang M, Hou Y, Ji Q, Zhang D (2020) Assessment and optimization of provincial CO<sub>2</sub> emission reduction scheme in China: An improved ZSG-DEA approach. *Energy Econ* 91: 104931.
22. Miao Z, Geng Y, Sheng J (2016) Efficient allocation of CO<sub>2</sub> emissions in China: a zero-sum gains data envelopment model. *J Cleaner Prod* 112: 4144-50.
23. Zhang YJ, Hao JF (2017) Carbon emission quota allocation among China's industrial sectors based on the equity and efficiency principles. *Ann Oper Res* 255: 117-40.
24. Yu A, Lin X, Zhang Y, Jiang X, Peng L (2019) Analysis of driving factors and allocation of carbon emission allowance in China. *Sci Total Environ* 673: 74-82.
25. Chu J, Shao C, Emrouznejad A, Wu J, Yuan Z (2021) Performance evaluation of organizations considering economic incentives for emission reduction: A carbon emission permit trading approach. *Energy Econ* 101: 105398.
26. Banker RD, Charnes A, Cooper WW (1984) Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Manag Sci* 30: 1078-92.
27. Kuosmanen T (2005) Weak disposability in nonparametric production analysis with undesirable outputs. *Am J Agr Econ* 87: 1077-82.
28. Lee CY (2018) Mixed-strategy Nash equilibrium in data envelopment analysis. *Eur J Oper Res* 266: 1013-24.
29. Ma CQ, Ren YS, Zhang YJ, Sharp B (2018) The allocation of carbon emission quotas to five major power generation corporations in China. *J Cleaner Prod* 189: 1-12.
30. Wan L, Du C (2021) An approach to evaluation of environmental benefits for ecological mining areas based on ant Colony algorithm. *Earth Sci Inform* 14: 797-808.
31. Cai W, Ye P (2019) A more scientific allocation scheme of carbon dioxide emissions allowances: the case from China. *J Cleaner Prod* 215: 903-12.
32. Cui X, Zhao T, Wang J (2021) Allocation of carbon emission quotas in China's provincial power sector based on entropy method and ZSG-DEA. *J Cleaner Prod* 284: 124683.
33. Han Y, Long C, Geng Z, Zhang K (2018) Carbon emission analysis and evaluation of industrial departments in China: an improved environmental DEA cross model based on information entropy. *J Environ Manage* 205: 298-307.
34. Li F, Emrouznejad A, Yang GL, Li Y (2020) Carbon emission abatement quota allocation in Chinese manufacturing industries: An integrated cooperative game data envelopment analysis approach. *J Oper Res Soc* 71: 1259-88.
35. Pang RZ, Deng ZQ, Chiu YH (2015) Pareto improvement through a reallocation of carbon emission quotas. *Renew Sust Energ Rev* 50: 419-30.

36. Xie Q, Hu P, Jiang A, Li Y (2019) Carbon emissions allocation based on satisfaction perspective and data envelopment analysis. *Energy Pol* 132: 254-64.
37. Zhonghua C, Yu S (2011) Environmental Protection Investment and Sustainable Development-Policy Simulation Based on Nonlinear Dynamics. *Energy Procedia* 5: 467-71.
38. Zhou P, Sun ZR, Zhou DQ (2014) Optimal path for controlling CO2 emissions in China: a perspective of efficiency analysis. *Energy Econ* 45: 99-110.

Submit your next manuscript to Annex Publishers and benefit from:

- ▶ Easy online submission process
- ▶ Rapid peer review process
- ▶ Online article availability soon after acceptance for Publication
- ▶ Open access: articles available free online
- ▶ More accessibility of the articles to the readers/researchers within the field
- ▶ Better discount on subsequent article submission

Submit your manuscript at

<http://www.annexpublishers.com/paper-submission.php>